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QUANTUM ENTANGLEMENT OF QUANTUM DOT SPIN USING FLYING QUBITS

UNIVERSITY OF MICHIGAN

MAY 2015

FINAL TECHNICAL REPORT

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14. ABSTRACT

This report summarizes the two years of support we received under the QuEST Program. The objective of the work has been to advance the frontier of quantum entangled semiconductor electrons using ultrafast optical techniques. The approach is based on semiconductor quantum dots doped with a single electron, made possible by the Coulomb blockade in this system. The quantum dots confine both electrons and holes and hence are optically active, enabling control of the quantum dot electron through the use of two-photon (Raman) transitions driven between the prepared electronic state to the final electronic state using the trion as a means to optically control the electronic state. The goal of the work has been to use photon interference methods to entangle electrons from different dots with inevitable differences in the frequencies of the emitted photons. The impedance matching between these two dots is mediated by photon interference using two entangled photons produced by spontaneous photon down conversion (SPDC) that can produce two entangled photons with their wavelengths tuned to match the wavelength of the photon produced by each dot.

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TABLE OF CONTENTS

LIST OF FIGURES

1.0 SUMMARY

This report summarizes the two years of support we received under the QuEST Program. The objective of the work has been to advance the frontier of quantum entangled semiconductor electrons using ultrafast optical techniques. The approach is based on semiconductor quantum dots doped with a single electron, made possible by the Coulomb blockade in this system. The quantum dots confine both electrons and holes and hence are optically active, enabling control of the quantum dot electron through the use of two-photon (Raman) transitions driven between the prepared electronic state to the final electronic state using the trion as a means to optically control the electronic state. The goal of the work has been to use photon interference methods to entangle electrons from different dots with inevitable differences in the frequencies of the emitted photons. The impedance matching between these two dots is mediated by photon interference using two entangled photons produced by spontaneous photon down conversion (SPDC) that can produce two entangled photons with their wavelengths tuned to match the wavelength of the photon produced by each dot. The report begins by summarizing the work we did during the beginning of the funding (started under previous DARPA funding) that resulted in a major publication demonstrating quantum entanglement of the polarization state of a spontaneously emitted photon resulting from radiative decay of a quantum dot trion with the spin of a single quantum dot electron spin produced by the trion decay. The report continues with progress toward demonstrating teleportation of information in the polarization state of a photon produced by high brightness SPDC source (developed by a collaboration with Prof. Kwiat at UIUC) to an electron spin in a quantum produced by the dot's spontaneously emitted photon. Teleportation occurs via detection of the appropriate quantum interference between the SPDC photon and the spontaneously emitted photon. Our work on this step in the program remains 'in progress' as the QuEST program ends.

2.0 INTRODUCTION

2.1 Background for research

The advanced understanding developed over the past 3 decades on the physics of optical interactions in III-V based photonic materials and the advanced materials processing capability to produce highly engineered structures have produced new devices with optical properties that are more diverse than other systems including atoms and molecules. The work in the last decade has shown the evolution of optical interactions that are dominated by many body physics in 2 and 3 dimensional structures to more atomic-like features in the quasi-zero-dimensional structures of self-assembled quantum dots. Unlike atoms that for a given isotope are all identical, one of the main challenges limiting full development of single dot based devices is to produce dots that are spatially and energetically within design specifications. This requires near-perfect growth to enable the engineering of dots to have optical features controllable at the level of 1 part in 10^6 and spatial positioning control on the order of 1 part in 10 relative to dot size:

numerous groups are working on this, including our collaborators at NRL and Würzburg, but advances in this area are coming slowly. Such control is needed for so-called hard-wired designs of quantum based architectures for either classical or quantum based information processing (see the proposal by our collaborator LJ Sham and his group in [1]). However, *recent progress by our group and others has shown the technology has advanced to the point that quantum dot structures could now be used to demonstrate scalable quantum computing architectures based on photon interference [2-5].*

2.2 Focus of the current program

Under this program, we worked to demonstrate the key building blocks and benchmark demonstrations for entanglement at a distance using quantum measurement. In this approach, a cluster of dots is produced (by our collaborators) in two separate cavities (planer or photonic crystal). Using Stark tuning and a magnetic field to adjust the center wavelength a dot is chosen from each cluster such that the two dots are as similar as possible. With two such dots having similar fluorescence lifetimes and polarization feature properties with no spectral wandering or extra dephasing, it is then possible to use the approach of Duan *et al.* [5]to entangle two electron spins by mixing the polarized fluorescence from the two dots on a polarization sensitive beam splitter. The approach to entanglement was first demonstrated by Moehring with Monroe [6]. This will be a major development for this quantum dot system and also provide a system to study decoherence between two dots entangled at a distance.

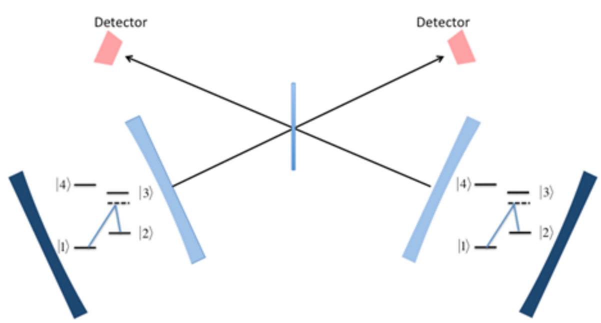

Figure 1. Schematic for entanglement of two spins based on measurement of the emitted photon from each excited state.

In the experiment, two dots separated by some distance much larger than a wavelength each spontaneously emit a photon following simultaneous optical excitation. The two photons then interfere on a beam splitter as shown in Fig. 1. The result is detected by two high quantum efficiency APDs or even more sensitive super conducting wire detectors. In a successful measurement each detector registers a single photon detected produced

By the photon state-vector $\left|\psi_p\right\rangle = (|h,v\rangle - |v,h\rangle)/\sqrt{2})$. The measurement leaves the two dots projected onto the maximally entangled state$|\psi_{dot}\rangle = (|X_+,X_-\rangle - |X_-,X_+\rangle)/\sqrt{2}$. This is basically teleportation of an entangled state, called the entanglement swapping protocol[5]. The quality of entanglement for quantum dots will depend in large part on the ability to overlap the fluorescence from the two dots where the concept of mode here includes the spatial and temporal properties as well as the degree of polarization, all of which can change slightly depending on the details the band structure. Working with structures developed from the same region of the same wafer will reduce but not eliminate this challenge.

A small difference in energy is also not an insurmountable challenge since we use a Raman configuration to do the transformation in a resonant cavity [7]. The cavity modes are adjusted to have the same frequency for the dots on two sides and laser tuning is adjusted to ensure the emitted photons will have the same frequency, making it possible for the impedance matching. However, this approach creates other challenges. Our approach in this program is use spontaneous photon down conversion which produces two hyperentangled photons to mediate the entanglement between the two dots.

In terms of scalability, the inhomogeneous effects become an integrated part, providing a tool to distinguish different dots through the frequency selection. We note that based on this architecture, it is possible to build a processor involving many dots, each entangled with other dots by measurement, an approached developed by one of our collaborators, Luming Duan [5] and proposed recently for quantum dots in [8]. With our discovery of optically induced nuclear spin fluctuation freezing [9, 10], the electron spin coherence times in dots are now sufficiently long (>microsecond) to enable a viable platform for bench mark studies.

2.3 Specific Aims/Objectives of current work

In the two years of funding we had from the QuEST Program, our objective has been to first demonstrate quantum entanglement between the spin of an electron confined to a single quantum dot with the spontaneously emitted photon that produces the spin state. Following Fig. 2, an example of this state is given by spontaneous emission of a photon from say the $|\mathrm{T}_{\mathrm{x}-}\rangle$ state leading to a quantum entangled state described by the state vector for the quantum dot given by $|\psi_{\mathrm{dot}}\rangle = (|\mathrm{H}, \mathrm{X}_{+}\rangle - |\mathrm{V}, \mathrm{X}_{-}\rangle)/\sqrt{2}$. This demonstration then sets the stage for demonstrating teleportation and wavelength conversion using photon interference with an entangled photon pair produced by a tunable approach using spontaneous photon down conversion (SPDC). The final demonstration is then to use the remaining photon from the SPDC to interfere with a spontaneously emitted photon from a second quantum dot and, after tuning the SPDC source, entangle the spin of the second dot with the first dot, again using photon interference. At the close of the QuEST program, the work is focused on demonstrating teleportation using the high brightness SPDC source being developed jointly with our collaborator, Prof. Paul Kwiat (UIUC). The work is divided into three clear tasks:

1. Demonstrate quantum entanglement between spontaneously emitted photon and the resultant two spin states that comprise the ground state of the charged dot;

2. Demonstrate teleportation of information to the quantum dot spin using quantum interference between the spontaneously emitted photon and information contained in a heralded single photon from an SPDC source and use this system to demonstrate wavelength conversion of the entangled photon spontaneously emitted from the charged quantum dot, especially to the wavelength of a second quantum dot and to telecom wavelengths (1.55 microns);

3. Demonstrate entanglement between two different electrons confined in two separated quantum dots operating at different frequencies.

3.0 METHODS, ASSUMPTIONS, AND PROCEDURES

The laboratory work is based on the use of self-assembled quantum dots that are doped with a single extra electron made possible by the Coulomb blockade. Samples using the Sharansky-Krasnow and molecular beam epitaxy. Charging control is by using inserting the dot in a PIN junction, Schottky diode or by using a delta-doping layer close to the dots. Dots are either bare or in a DBR cavity. Samples are provided by our collaborators Dan Gammon and Alan Bracker at NRL and Sven Höfling at Würzburg/St. Andrews.

For these studies, the energy level structure for the charged quantum dot is shown in Fig. 2 where optical selection rules are provided assuming a magnetic field is applied in the x-direction (Voigt profiles, where the z-direction parallel to the direction of MBE growth). High speed state initialization is achieved by spin cooling techniques demonstrated earlier on DARPA support by us [11, 12].

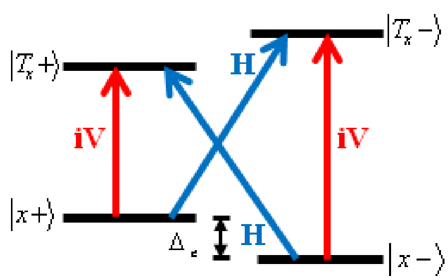

Figure 2. Energy level diagram for a negatively charged QD in a magnetic field in the Voigt geometry with linearly polarized light along the red and blue transitions.

To demonstrate entanglement between a spin and a photon, we needed to achieve a high level of laser rejection. To this end, we developed a new optical setup which achieves extremely high polarization extinction ratio (exceeding 10^6 x) while maintaining high collection efficiency of spontaneously emitted photons. In doing so, we eliminated the metal apertures used previously to optically isolate single quantum dots, and adopted a high NA confocal fiber setup that allows for single quantum dot resolution and the required high polarization extinction ratio.

The result is our ability to directly measure the resonance fluorescence produced by excitation of laser on resonance. Our approach completely rejects the incident laser field. This enables the direct detection (without signal processing) of the resonant Rayleigh scattering from the dot. The data is shown in Fig. 3, obtained looking directly down the axis of excitation and using the high polarization contrast to reject the excitation field. The data shown is obtained directly, without use of the usual lock-in detection methods. The background is observed to be very small compared to the scattering and is more than adequate to enable demonstration of high quality entanglement. Using time to digital histogramming with fast APDs, we have the needed timing resolution for the demonstration.

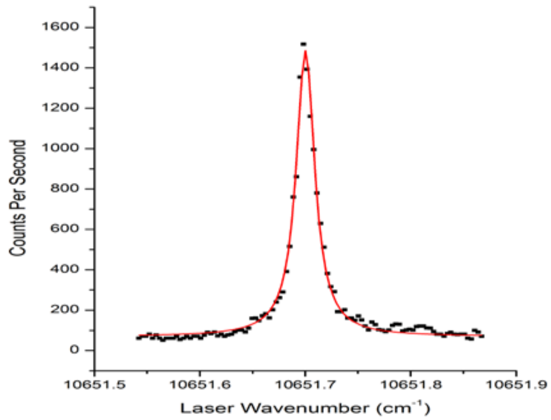

Figure 3. Resonance fluorescence from a single quantum dot under narrow bandwidth CW excitation. The red line is a Lorentzian fit of the data. No modulation or background subtraction has been performed.

4.0 RESULTS AND DISCUSSION

4.1 Spin-Photon Entanglement

Measurements were completed showing entanglement between a quantum dot (QD) and its emitted photon. The measurements were the culmination of over two years of work developing new photon counting and detection techniques. These experiment were performed using a single electron confined to an Indium Arsenide (InAs) QD. When placed in a magnetic field, the electron spin provides the two level ground state necessary for quantum-computing architectures, more commonly referred to as a quantum bit (qubit). The excited states of the system create an effective 4-level system shown in the figure.

If we excite the system to the $|T_x -\rangle$ state, spontaneous decay will create an entangled state of the emitted photon's polarization and the spin state of the QD. For example if a V-polarized photon is emitted we know that the spin is $|X -\rangle$. Prior to measurement this leads to an entangled state of the form, $|\Psi\rangle = |H\rangle|x +\rangle - i|V\rangle|X -\rangle/\sqrt{2}$.

To demonstrate the entangled state, we performed experiments showing the correlation between emitting a photon of a certain polarization (e.g. V) and the spin being in the correlated state (e.g. x-). We also must show that the coherence in preserved in a rotated basis. To do this, we rotated the polarization basis by using circularly polarized light and rotate the spin basis by looking at the z-basis, which is a linear combination of the x states. When a photon is emitted in the rotated basis a time dependent phase accumulates at the frequency of the electron splitting (Δ_e). We use a detuned Raman pulse to rotate the coherence into a population and the phase accumulation stops. So, the timing resolution must be better than $1/\Delta_e$ so we can observe the phase accumulation. This creates an experimental challenge since the best timing resolution for most detectors is 50ps, setting a limit on how large we can make the electron splitting. The lower the magnetic field we use the harder it is to selectively excite certain transitions and purify the initial state. Using CW lasers gated by electro-optic modulators (EOM) we can time gate our excitation while still using narrow linewidth lasers for transition selectivity. All of the timing electronics (EOMs, detectors and the Raman pulse) must be synced to a master clock throughout the 30-hour runtime. When we analyze the data we see the characteristic coherence fringes expected at the spin difference frequency, shown below (Fig. 4) for the two different circular polarizations. In Fig. 4 we show the time resolved coincidence oscillations showing the QD spin

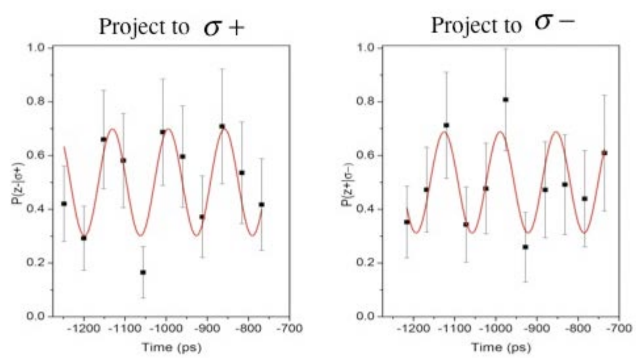

Figure 4. Time resolved coincidence oscillations showing the QD spin coherence.

coherence generated by projecting of the photon state onto $\sigma\pm$ for the left and right figures, respectively. The time axis is taken relative to the QD spin rotation pulse which occurs at t = 0. The first three periods of the normalized data are fit to Eq. (2) using the experimentally determined difference frequency (7.35 GHz). The data show fringe contrasts of 0.40 ±.10 for $\sigma+$ and 0. 38 0.08 for $-$.

These measurements combined with the others detailed in our publication [13] enable measurements of all the correlations in both the measurement and computational basis shown in Fig. 5.

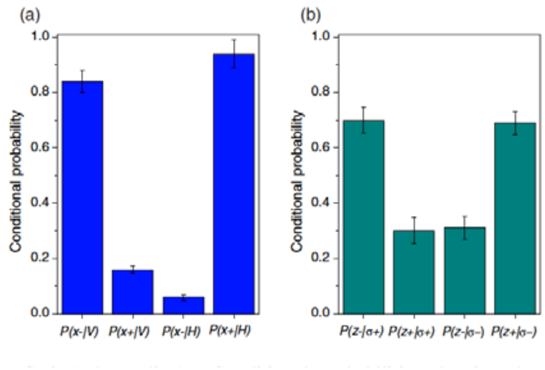

Figure 5. Conditional probabilities showing the correlated nature of the entangled spin-photon state in two bases. (a) For the H,V measurements, corrected data are shown. (b) For the measurements, the conditional probabilities are extracted from fits shown in Fig. 4.

While the details are given in [13], we note that by convolving the theoretical signal with the detection system's instrument response function, and assuming a perfect correlation in the x basis, we estimate our experimentally realizable fidelity to be ~0.7, putting the measured fidelity bound at 84% of the detector limited bound. The deviation from 100% of the maximum achievable fidelity is primarily from imperfect state initialization which is most pronounced in the V polarized (x basis) measurements.

During this period, we also completed and published a design[14] and a preliminary demonstration of deterministic entanglement[15] based on the work of our collaborator Prof. LJ Sham and his students[16].

4.2 Teleportation of information in SPDC photon to a single quantum dot electron spin.

With the first objective completed, we then started work on the second task which included beginning a collaboration with Prof. Paul Kwiat at UIUC to demonstrate teleportation of information contained in the polarization of a photon produced by spontaneous photon down conversion (SPDC). The collaboration is unique because our two groups have joined together to produce a high brightness SPDC source, developed by Prof. Kwiat and his students. The high brightness source (the SPDC crystals are in a cavity) enable a shorter data acquisition time demonstrate teleportation. The information in the SPDC photon is teleported to a single quantum dot spin by a projective measurement using a Hong Ou Mandel (HOM) interferometer. The SPDC source emits two photons which are entangled in both wavelength and polarization. The second photon is used either to herald the first photon in a teleportation measurement to change the wavelength of the quantum dot entangled photon to a wavelength matching a second quantum dot (typically at 960nm) or to a telecom wavelength (e.g., 1.55microns) for long distance transmission. .

Figure 6 shows the experimental configuration and timing diagram for the general experimental setup. Figure 7 provides a more detailed description of the HOM measurement that establishes entanglement.

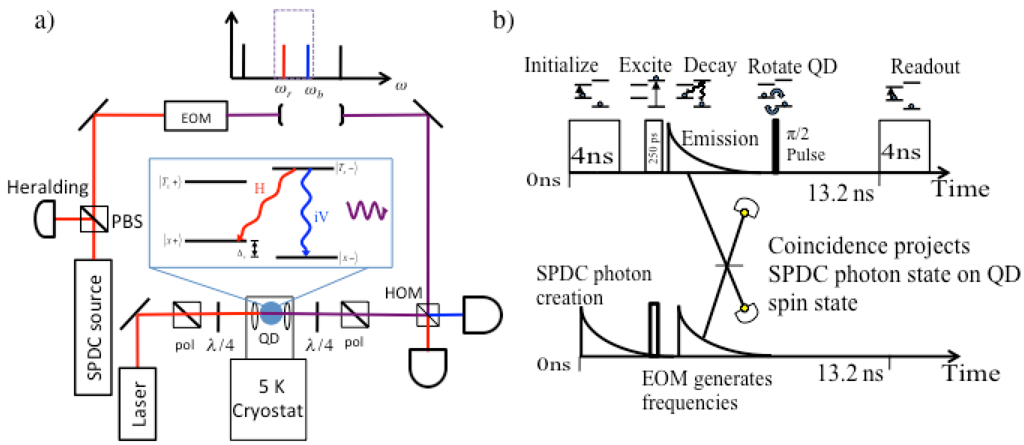

Figure 6. (a) Optical diagram for teleportation experiment, (b) Timing diagram for the experiment.

To understand the experiment, the state vector for a photon undergoing spontaneous radiative decay to one of two spin sates and the state vector for SPDC photon are given by

$$\left|\psi\right\rangle_{1QD} = \frac{1}{\sqrt{2}}\left(\left|R\right\rangle_1 \left|x+\right\rangle_{QD} + \left|B\right\rangle_1 \left|x-\right\rangle_{QD}\right) \tag{1}$$

$$\left|\phi\right\rangle_2 = \frac{1}{\sqrt{2}}\left(C_r\left|R\right\rangle_2 + C_b\left|B\right\rangle_2\right) \tag{2}$$

where R and B represent say red and blue, respectively. Upon coincident detection in the HOM we know that the photons emerged from different paths and were therefore in different modes. However, there is no way to determine which input photonic qubit emerged on a given side, this leads to a projection of the photons to an intermediate anti-symmetric entangled state.

$$\left|\phi\right\rangle_{12} = \frac{1}{\sqrt{2}}\left(\left|R\right\rangle_1\left|B\right\rangle_2 - \left|B\right\rangle_1\left|R\right\rangle_2\right) \tag{3}$$

Where the photonic states are now orthogonal to each other requiring the initial state of photon 2 be instantly teleported onto $\left|\psi\right\rangle_{QD}$ giving,

$$\left|\psi\right\rangle_{QD} = \frac{1}{2}\left(C_b\left|x+\right\rangle_{QD} - C_r\left|x-\right\rangle_{QD}\right). \tag{4}$$

By manipulating the initial state of photon 2 (the prepared photon), changing the relative values of C_r and C_b, which are complex variables, we can control the resulting spin state of the QD. A readout of one of the spin states as a function of the changing coefficients on the prepared photon state will signify successful teleportation.

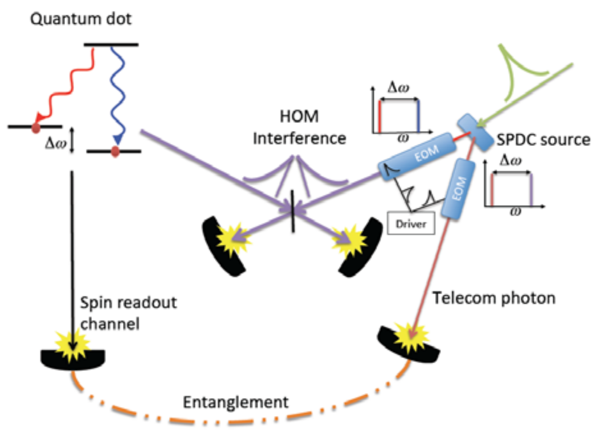

Figure 7. The teleportation measurement details.

In Fig. 7 the teleportation measurement will be extended to enable shifting wavelength of an entangled photon. This is made possible since SPDC produces an EPR pair where the frequency of each can be tuned. The experimental approach to shifting the wavelength of entangled spin-photon from the wavelength of the spontaneously emitted photon (around 960nm) to the telecom region (1.55μm)

5.0 CONCLUSIONS

The objective of this work was to advance the state of the art in the application of charged quantum dots for quantum computing. Given the heterogeneity of quantum dots, our approach is based on a reasonably robust method of inter-dot entanglement using photon interference. A SPDC source of photons produced entangled photon with tunable wavelengths for both the signal and the idler. Hence, these two frequencies can be adjusted match the frequencies of the spontaneously emitted photons from each dot. This approach has the advantage of also providing a means to shift the wavelength of the spontaneously emitted photon from a dot from the usual wavelength, around 960nm, to telecom wavelength (1.55 microns) for long distance transmission in fibers. Work toward these goals began with non QuEST support from DARPA but was completed with support from QuEST. This was the experiment to demonstrate quantum dot spin entanglement with the spontaneously emitted photon. At the close of this program, we continue to work toward demonstrating entanglement between a photon generated by a high brightness source. Work is progressing well, and will continue as funds are available. A key step in this process has been the initiation of work with quantum dots contained in low finesse cavities that increase the brightness of the dots, often by a few orders of magnitude. An example from our laboratory of the increase in brightness is shown in Fig. 8 where the photoluminescence produced by our previous structures and the new structures.

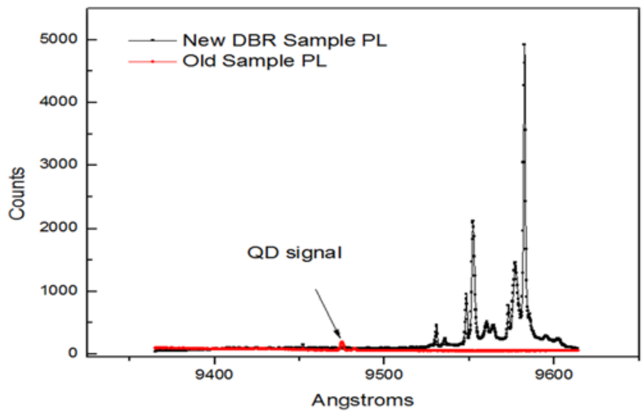

Figure 8. Comparison of the photoluminescence observed in a 'bare' quantum dot ("Old Sample" and the new sample where the dots are grown inside a DBR cavity (New DBR Sample).

During this period, the following papers were published based on work supported by this program:

1. Katherine Truex, Leon Webster, L.-M. Duan, L. J. Sham, and D. G. Steel "Coherent Control with Optical Pulses for Deterministic Spin-Photon Entanglement" Phys. Rev. B.88, p195306 (2013). http://journals.aps.org/prb/abstract/10.1103/PhysRevB.88.195306

2. J. R. Schaibley, A. P. Burgers, G. A. McCracken, and D. G. Steel_ A. S. Bracker and D. Gammon L. J. Sham, "Direct Detection of Time Resolved Rabi Oscillations in a Single Quantum Dot via Resonance Fluorescence", Physical Review B **87** p115311 (2013). **DOI:** 10.1103/PhysRevB.87.11531,http://journals.aps.org/prb/abstract/10.1103/PhysRevB.87.115311

3. J. R. Schaibley, A. P. Burgers, G. A. McCracken, L-M Duan, P. R. Berman, and D. G. Steel, A. S. Bracker and D. Gammon L. J. Sham, "Demonstration of quantum entanglement between a single quantum dot electron spin and a photon", Physical Review Letters **110**, 167401 (2013). http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.110.167401, **DOI** 10.1103/PhysRevLett.110.167401,

4. L. A. Webster, K. Truex, L.-M. Duan, D. G. Steel, A. S. Bracker, D. Gammon, and L.J. Sham, "Coherent control to prepare an InAs quantum dot for spin-photon Entanglement," Phys. Rev. Lett. **112**, 126801 (2014). DOI: 10.1103/PhysRevLett.112.126801

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7.0 LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

APD:	Avalanche photo diode
B:	Blue
CW:	Continuous wave
DBR:	Distributed Bragg reflector
EOM:	Electro-optics modulator
H:	Horizontal
HOM:	Hong-Ou-Mandel
InAs	Indium Arsenide
NA:	Numerical Aperture
QD:	Quantum Dot
SPDC:	Spontaneous photon down conversion
R:	Red
V:	Vertical